

**STATUS REPORT AND PRELIMINARY RESULTS OF THE
SPACECRAFT CONTROL LABORATORY EXPERIMENT**

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INTRODUCTION

The Spacecraft Control Laboratory Experiment (SCOLE) has been conceived to provide a physical test bed for investigation of control techniques for large flexible spacecraft. The SCOLE problem is defined as two design challenges. The first challenge is to design control laws for a mathematical model of a large antenna attached to the space shuttle by a long flexible mast. The second challenge is to design and implement a control scheme on a laboratory representation of the structure modelled in the first part. Control sensors and actuators are typical of those which the control designer would have to deal with on an actual spacecraft. The primary control processing computer is representative of the capacity and speed which may be expected in actual flight computers. This paper gives a brief description of the laboratory apparatus and some preliminary results of structural dynamics tests and actuator effectiveness tests.

INTRODUCTION

- * EXPERIMENT CONCEIVED TO PROVIDE A COMMON
"DESIGN CHALLENGE" FOR INTERESTED INVESTIGATORS
- * SLEWING AND POINTING CONTROL PROBLEM
- * USES ANTENNA LIKE STRUCTURAL CONFIGURATION AND INERTIAL
SENSORS AND ACTUATORS
- * VARIETY OF SENSOR AND ACTUATOR TYPES
 - Accelerometers, rate sensors, optical position
 - Thrusters, cmg, reaction wheel
- * MULTI-MICROPROCESSOR BASED COMPUTING

CONTROL PROBLEM

The control problems to be studied are slewing and pointing maneuvers. The slew is defined as a minimum time maneuver to bring the antenna line-of-sight (LOS) pointing to within an error limit δ of the pointing target. The second control objective is to rotate about the line of sight and stabilize about the new attitude while keeping the LOS error within the bound δ .

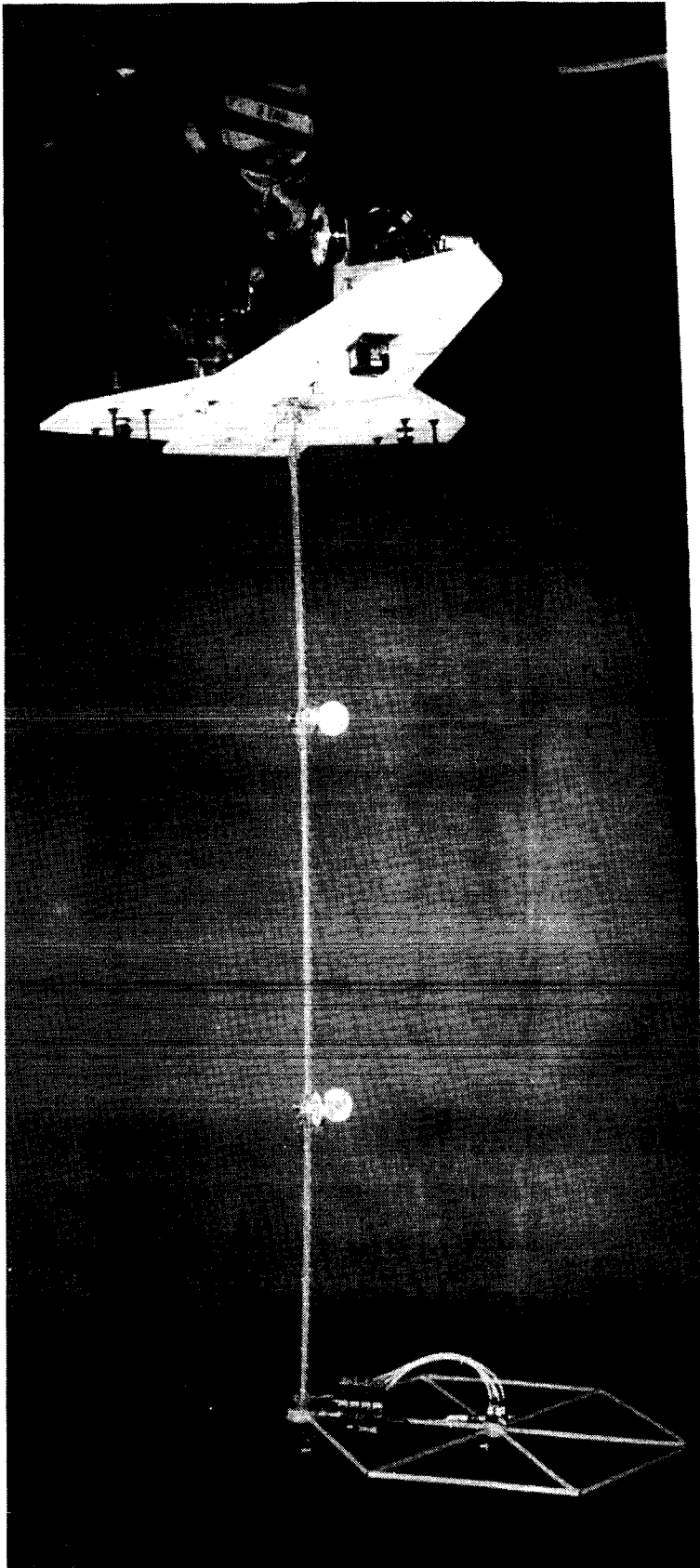
CONTROL PROBLEM

- * PRIMARY - SLEW 20 DEGREES ABOUT MINIMUM AXIS OF INERTIA
LINE-OF-SIGHT (LOS) POINTING WITHIN .02 DEGREES RMS
- * SECONDARY - ROTATE ABOUT LOS WHILE MAINTAINING POINTING
ACCURACY

LABORATORY APPARATUS

The laboratory experiment shown in the slide attempts to implement the definition of the math model design challenge within reasonable limits of the lg, atmospheric environment. The experimental facility exhibits the essential SCOLE characteristics of a large mass/inertia connected to a small mass/inertia by a flexible beam. Some trades are made in terms of structure, sensors, actuators, and computational capability in order to develop the experiment in a timely and cost effective manner. To this end, the basic structure is made of homogeneous continuous elements. It is suspended from a steel cable with the positive z-axis of the shuttle pointing up, thus minimizing the static bending of the antenna mast. The suspension point is a two-degree-of-freedom gimbal for pitch and roll with yaw freedom supplied by the suspension cable. The sensors are aircraft quality rate sensors and servo accelerometers. An optical sensor is available for attitude determination. The shuttle based control moments are provided by a pair of 2-axis control moment gyros. The mast mounted control torques are provided by two-axis reaction wheels. Reflector based forces are provided by solenoid actuated cold air jets. Computational facilities consist of micro-computer based cpu's with appropriate analog interfaces, and a hybrid computer for control of the control moment gyros. The elements which make up the SCOLE experiment are described in detail in the following text.

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STRUCTURES

The Spacecraft Control Laboratory Experiment is comprised of three basic structures: the shuttle, the mast, and the reflector panel. The assembly of these individual components is shown in the slide.

The shuttle planform is made from a 13/16 inch steel plate and has overall dimensions of 83.8 by 54.0 inches. Its total weight is 501.7 pounds. The shuttle's center of mass is located 3.4 inches below the experiment's point of suspension, and 26.8 inches forward of the tail edge.

The mast is 120 inches long. It is made from stainless steel tubing and weighs 4.48 pounds. One-inch thick manifolds are mounted to the mast at each end.

The reflector panel is hexagonal in shape, made from welded aluminum tubing, and weighs 4.76 pounds. It is located 126.6 inches below the SCOLE's point of suspension. The center of the reflector is located at 12.0 inches in the x direction and 20.8 inches in the y direction from the base of the mast.

STRUCTURAL DETAILS

* ESSENTIAL CHARACTERISTICS

SHUTTLE \Rightarrow LARGE MASS/INERTIA

MAST \Rightarrow FLEXIBLE, CONTINUOUS BEAM

REFLECTOR \Rightarrow SMALL MASS/INERTIA

FREE BOUNDARY CONDITIONS

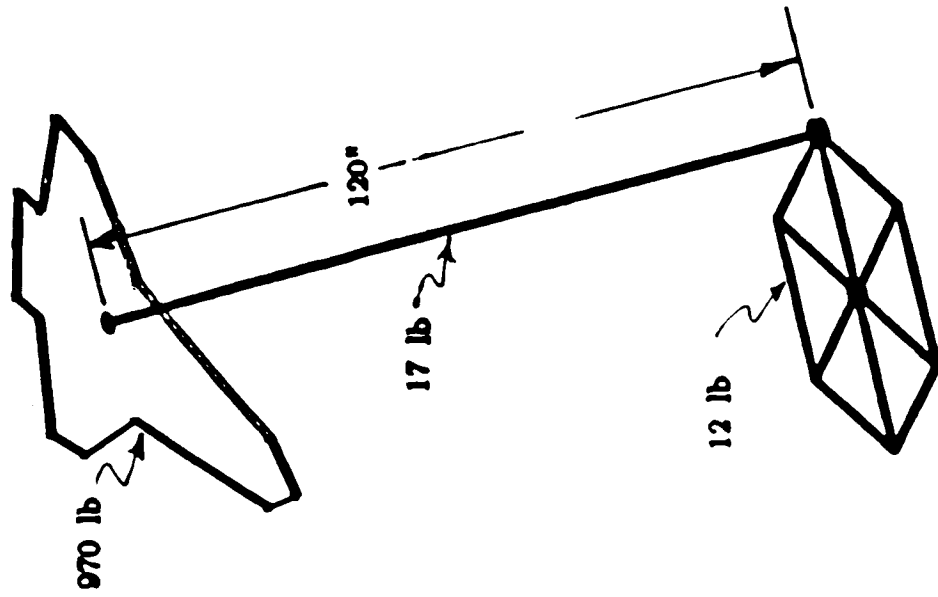
* SATISFIED BY:

SHUTTLE \Rightarrow 3/4" STEEL PLATE WITH
WEIGHTS ADDED TO
INCREASE MASS/INERTIA

MAST \Rightarrow 3/4" x .049" STEEL TUBE

REFLECTOR \Rightarrow ALUMINUM TUBE FRAME

PENDULUM WITH UNIVERSAL JOINT
(5 DOF)



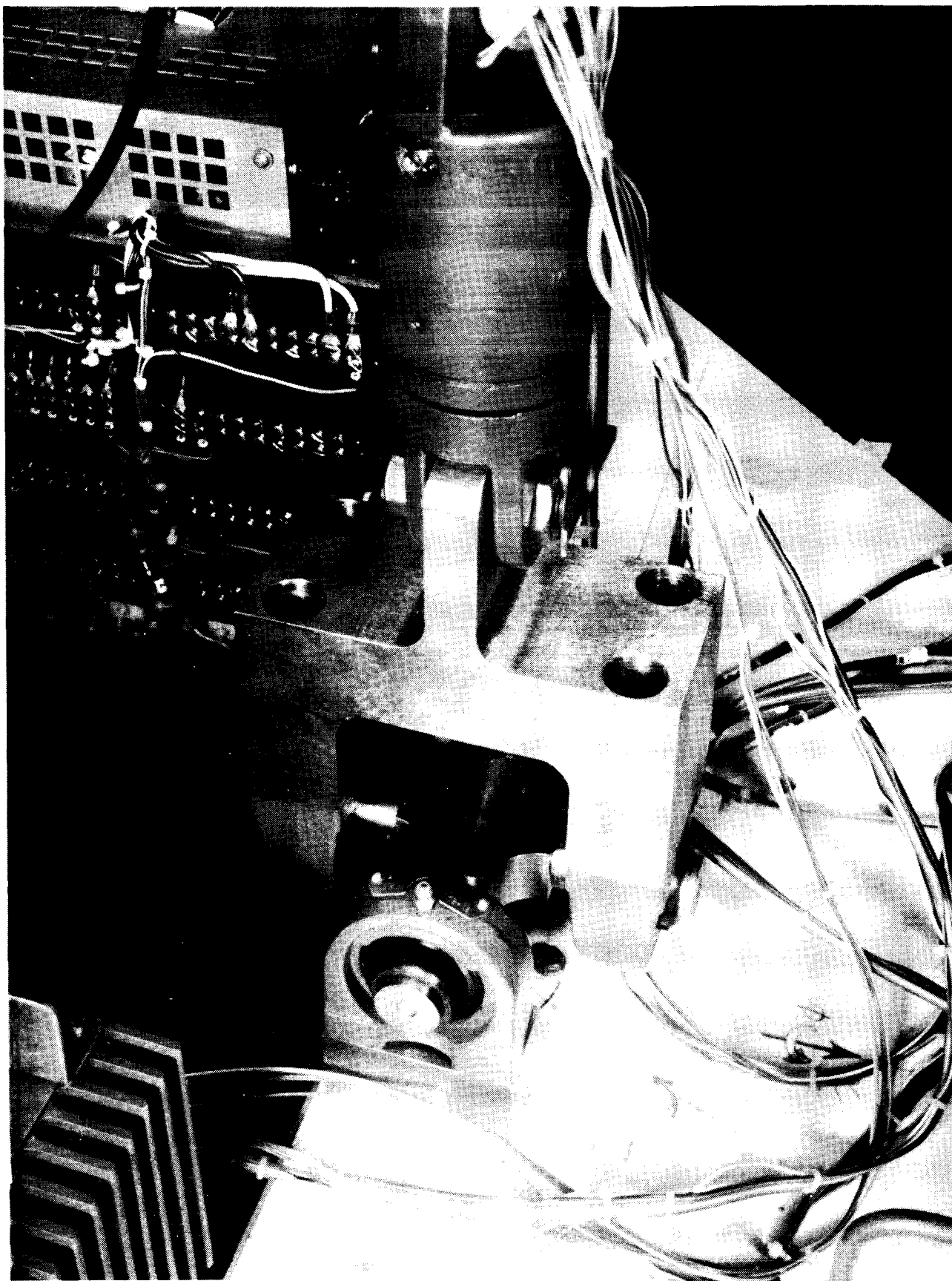
SUSPENSION

The complete system is suspended from an 11-foot cable attached at the system center of gravity via a universal joint. Roll and pitch rotational freedom is provided by pillow block ball bearings which have an estimated break-out torque of .1 ft-lb. The universal joint is fixed to the shuttle plate and the center of gravity is made to coincide with the center of rotation by means of an adjustable counter balance system.

SENSORS

The sensors for the experiment consist of nine servo-accelerometers and two, three-axis rotational rate sensing units. The power supplies for the sensors are mounted on the shuttle plate to minimize the number of large gage wires which must cross the universal joint suspension point. Only a single 115 VAC wsource and the signal wires cross the universal joint. The wires for the sensors are routed on the shuttle and along the mast.

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SENSORS

TYPE LOC.	3 AXIS RATE GYRO	2 AXIS ACCELERATION	3 AXIS ACCELERATION
SHUTTLE	X		X
MAST	X	2 places	
REFLECTOR		X	

* Rate gyros

60 and 360 deg/sec range
flat response to 10 Hz

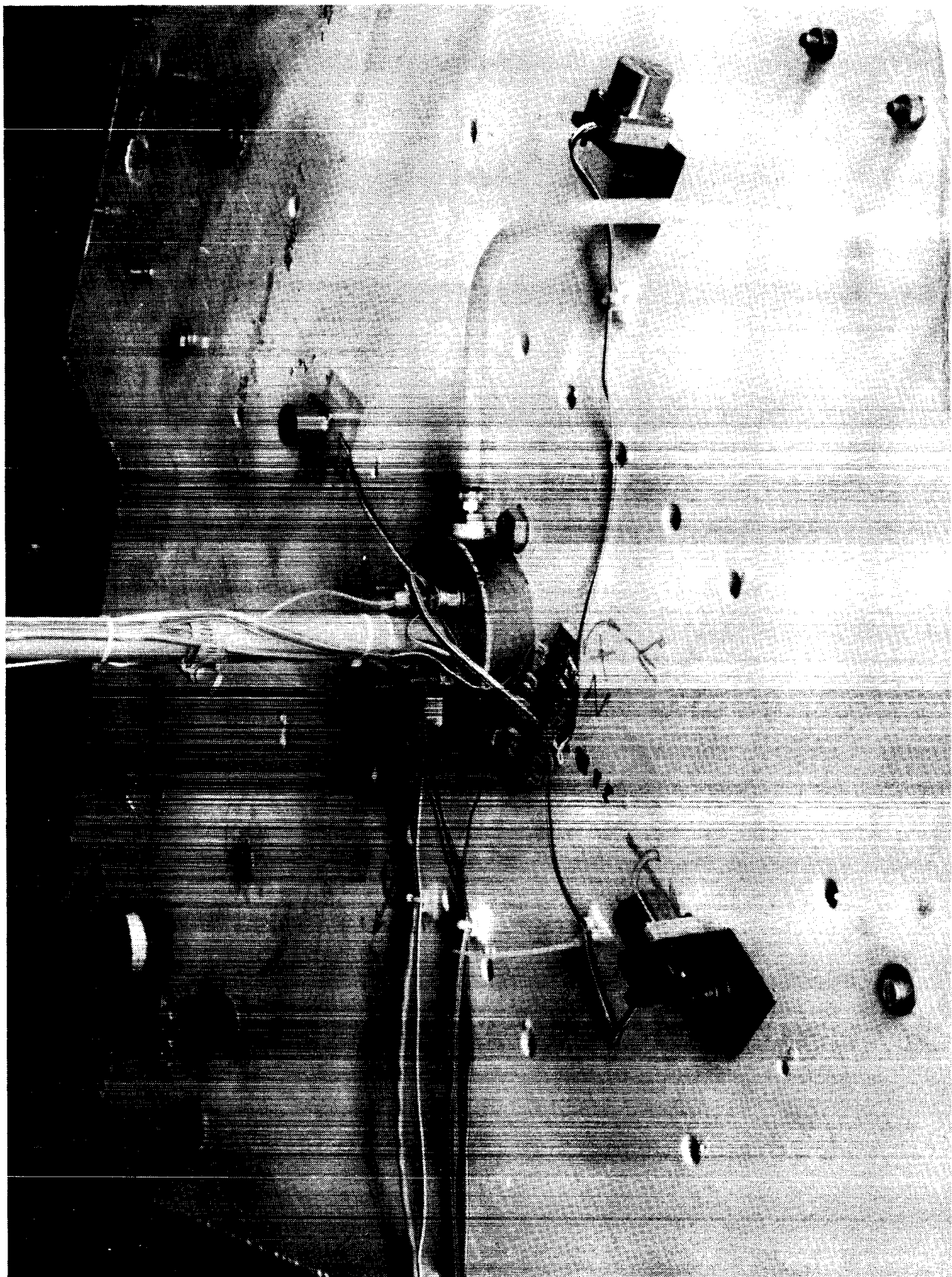
* Accelerometers

+/-20 g range, 5 micro-g threshold
flat response to 50 Hz

ACCELEROMETERS

The shuttle-mounted accelerometers shown in the slide sense the x, y, and z acceleration. They are distributed away from the suspension point to aid inertial attitude estimation. All nine accelerometers have a frequency response which is nearly flat up to 350 Hz.

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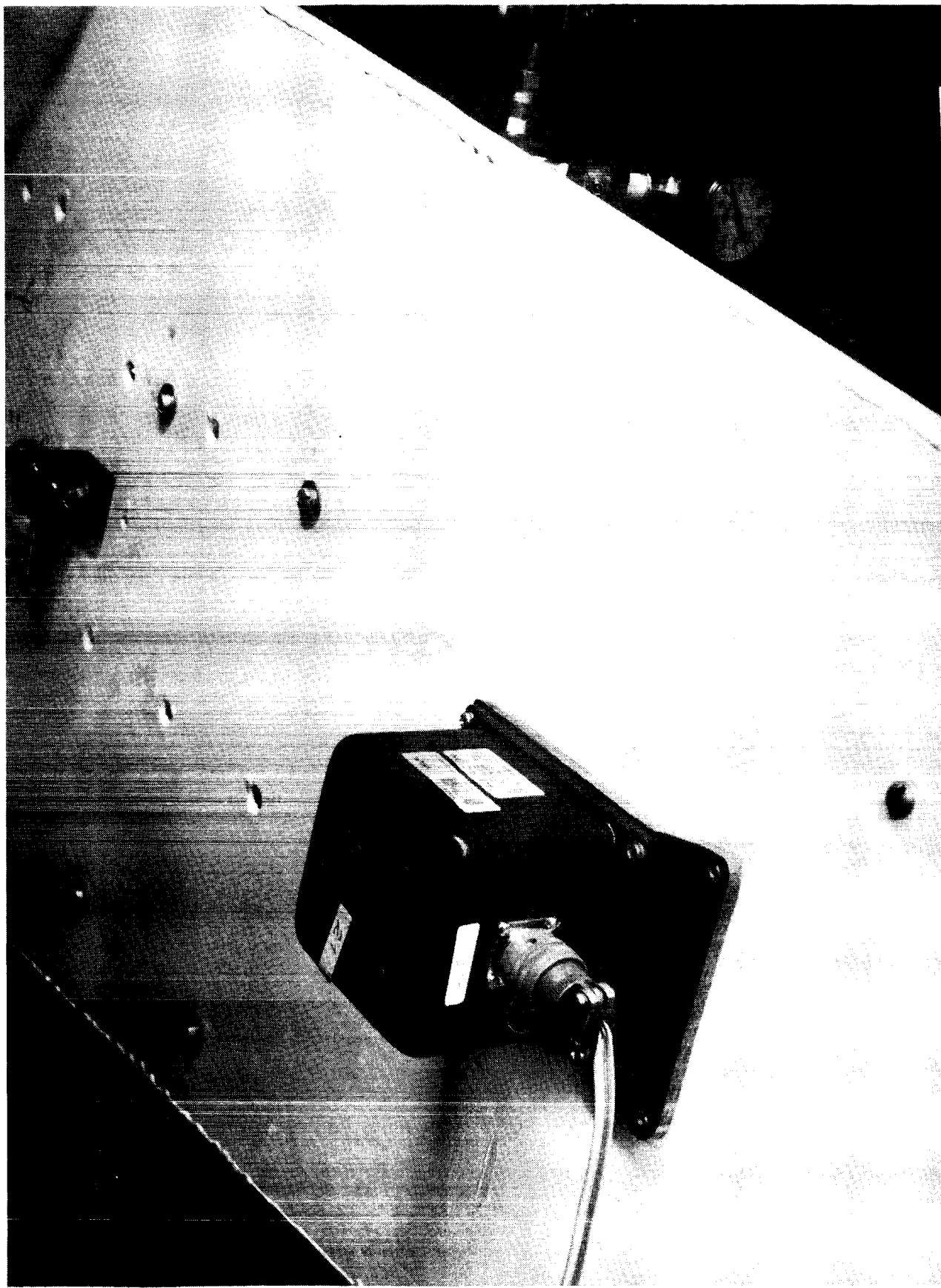


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RATE SENSORS

The shuttle-mounted rate sensor package shown in the slide senses three axis rigid body angular rates of the shuttle plate. The rotational rate sensors are three axis aircraft quality instruments. The frequency response is approximately flat to 1 Hz and -6 db at 10 Hz. Linearity is about .6 percent full scale. The range is 60 deg/sec for the yaw and pitch axes and 360 deg/sec for roll. A rate sensor package mounted at the end of the mast senses three axis angular rates at the reflector end of the mast.

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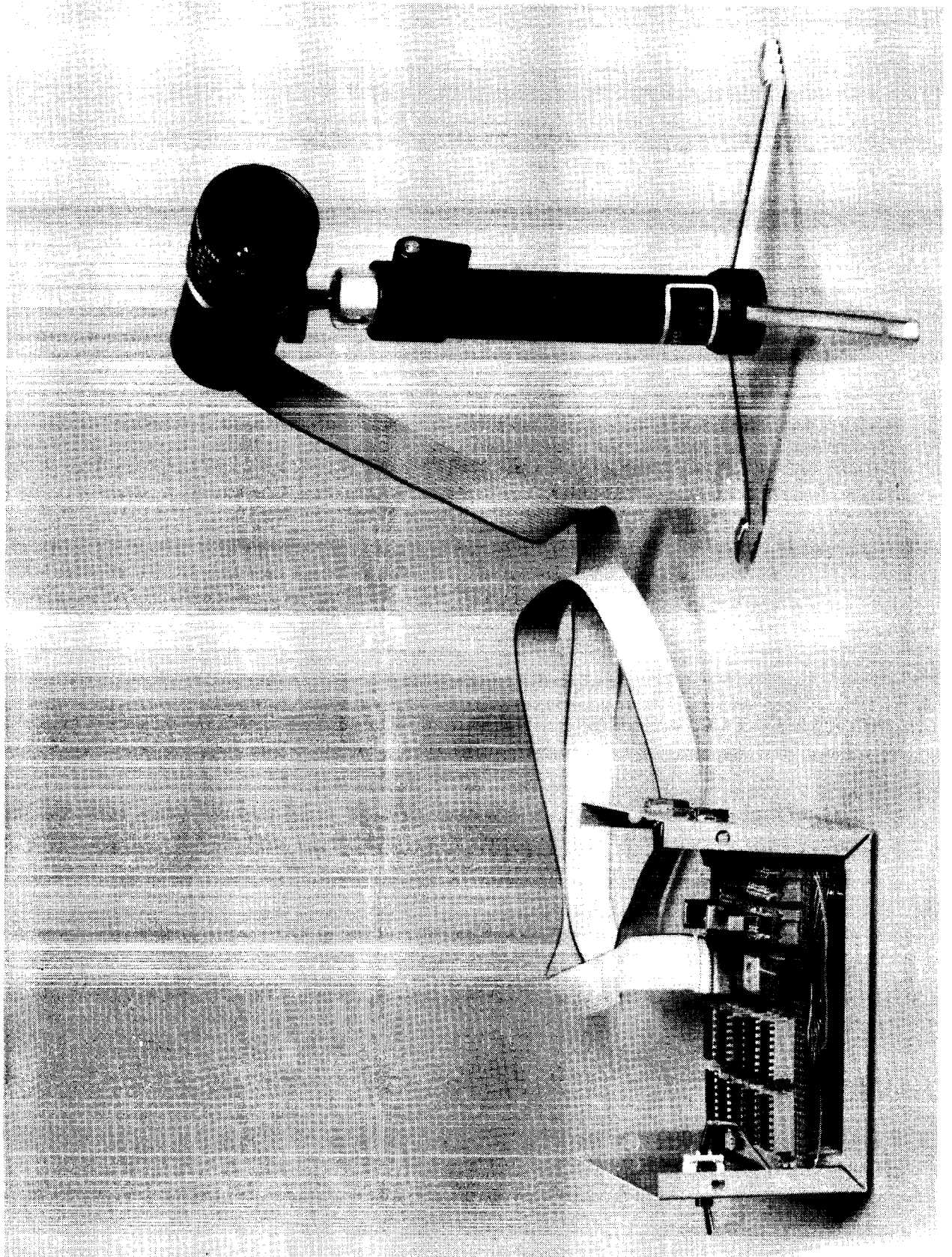
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OPTICAL SENSOR

An optical sensor based on an optically sensitive 65-kbit dynamic memory chip has been developed. It is capable of measuring two-dimensional position with about 0.5 percent resolution and can communicate the position data to the host computer over a serial data link. An Intel 8751 micro-controller is used to program the refresh rate of the memory cell and detect the optical image. A point of light is sensed by first filling the memory with ones. Then the refresh is disabled for a pre-determined amount of time so that the cells exposed to the light will change to a zero state. The 8751 then scans the entire array to determine the location of the point of light. It then transmits the position and rescans a sixteen by sixteen square area around the last position and again transmits the detected position.

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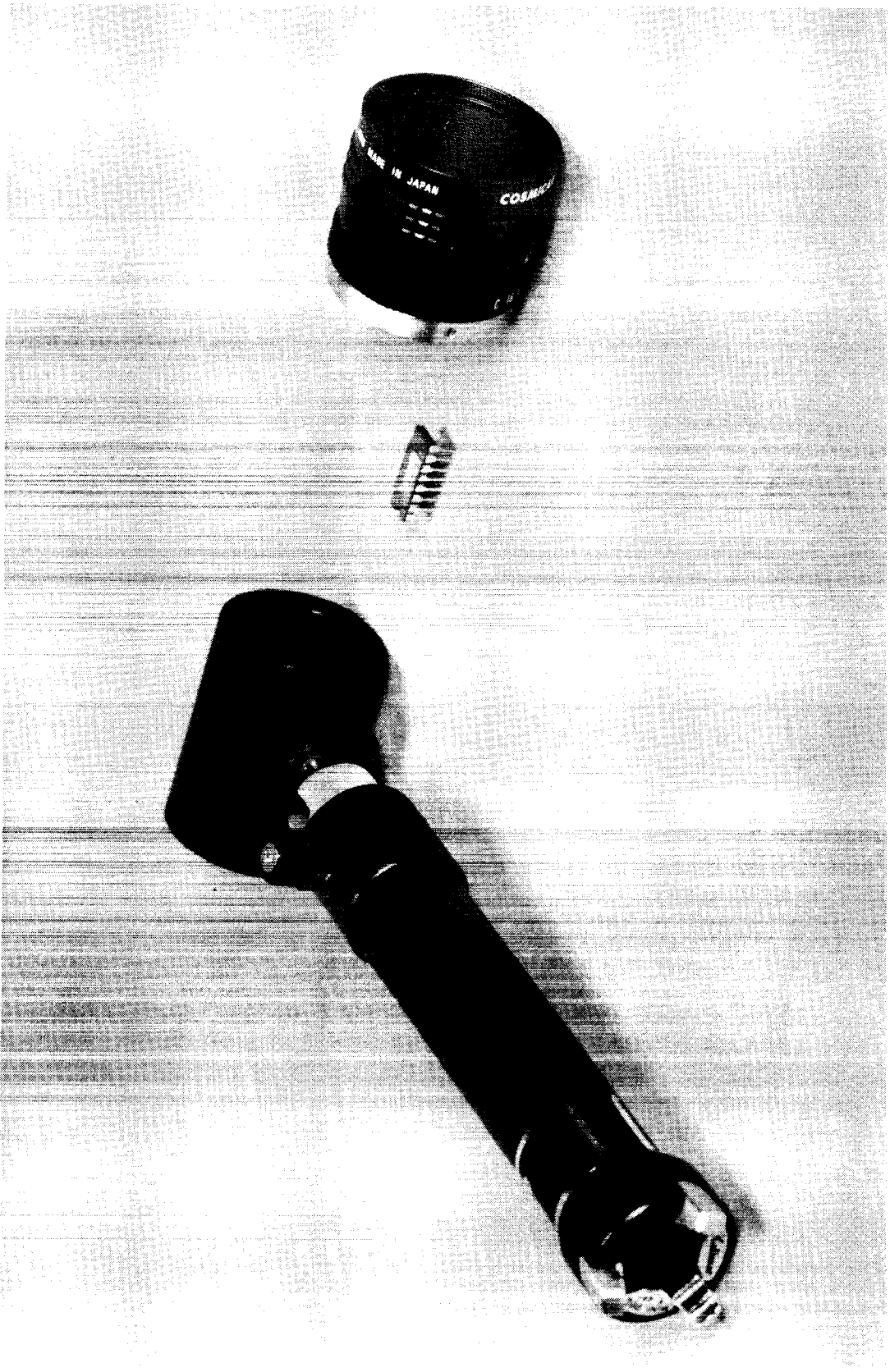
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DYNAMIC MEMORY CHIP

The memory chip shown in the center of the slide is not without disadvantages. The map of the memory cells is not uniform there are a number of dead zones around each memory cell and the address map is interlaced rather than one-to-one. Also the image plane is divided into two halves by a dead zone of about 20 percent of the total imaging width.

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ACTUATORS

The actuators consist of both proportional and on-off controllers. Shuttle attitude control is provided by a pair of two-axis control moment gyros (CMG). Mast vibration suppression is provided by a pair of two-axis reaction wheels. Reflector forces are provided by four cold gas jets. As with the sensors, all devices are inertial, and the power supplies and amplifiers are mounted on the shuttle. All actuators were manufactured in house.

ACTUATORS

TYPE LOC.	2 AXIS CMG	2 AXIS REACTION WHEEL	2 AXIS THRUST
SHUTTLE	2 places		
MAST		2 places	
REFLECTOR			X

* CMG

1.8 ft-lb gimbal torque
.337 in-lb-sec momentum
flat frequency response to 1kHz (est.)

* Reaction wheel

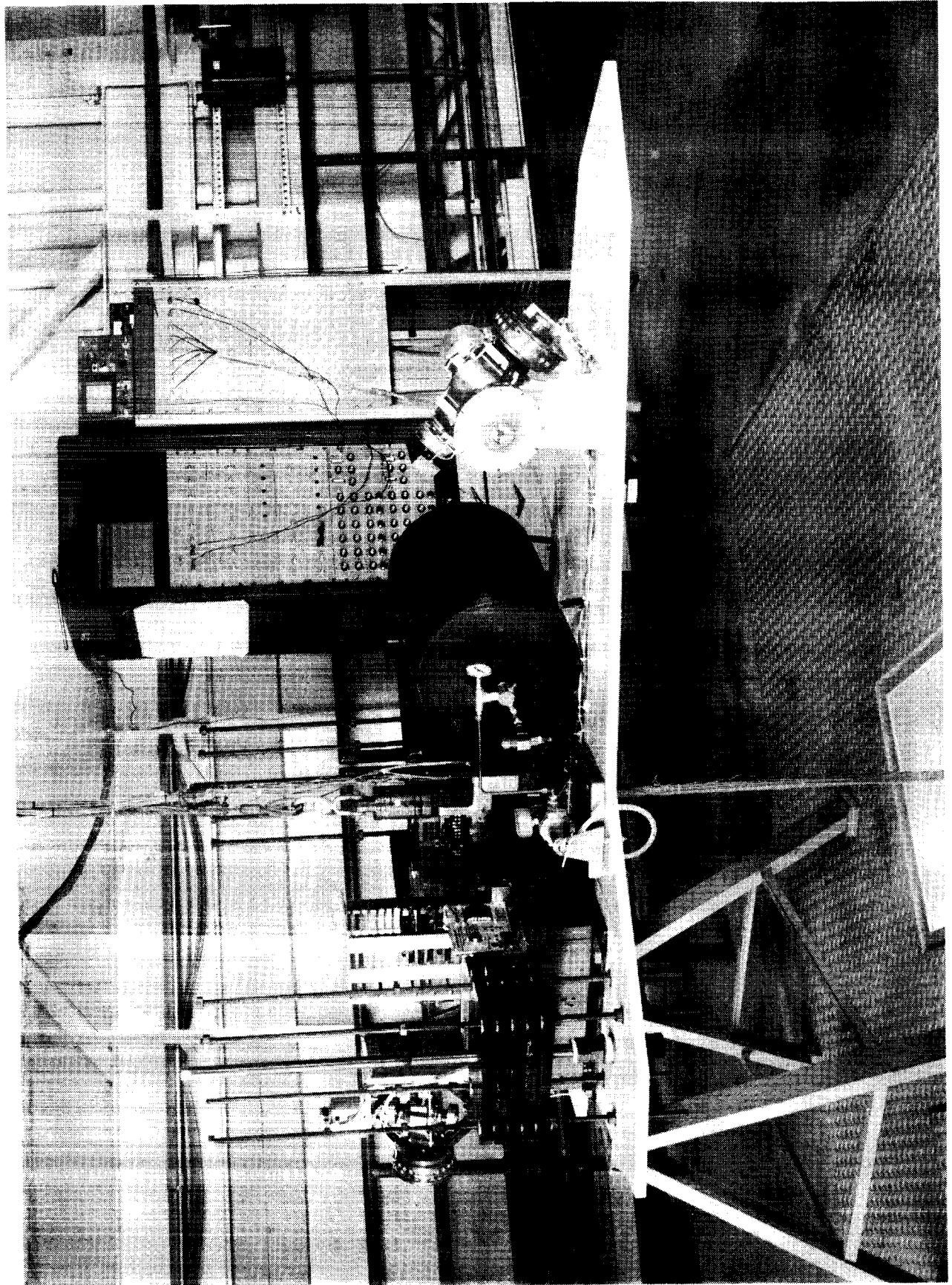
20 oz-in torque
flat frequency response to 1kHz (est.)

* Thrust

.5 lb for 15 seconds
.023 second rise time

CONTROL MOMENT GYROS

A pair of two-axis control moment gyros (cmg's) are mounted on the shuttle plate to provide three axis torques. The CMG's each have two gimbals which are direct driven by individual DC torque motors. The momentum wheel is mounted in the inner gimbal and is driven by two permanent magnet DC motors. The nominal momentum is about 2.5 ft-lb-sec. The gimbal torque motors are driven by current amplifiers so the output torque will be proportional to the command voltage sent to the power amplifier. The gimbal torquers will produce ± 1.5 ft-lb at frequencies up to 1 kHz. The gimbals are instrumented with tachometers and sine-cosine pots to allow decoupled control of the shuttle attitude angles in a precision command mode.



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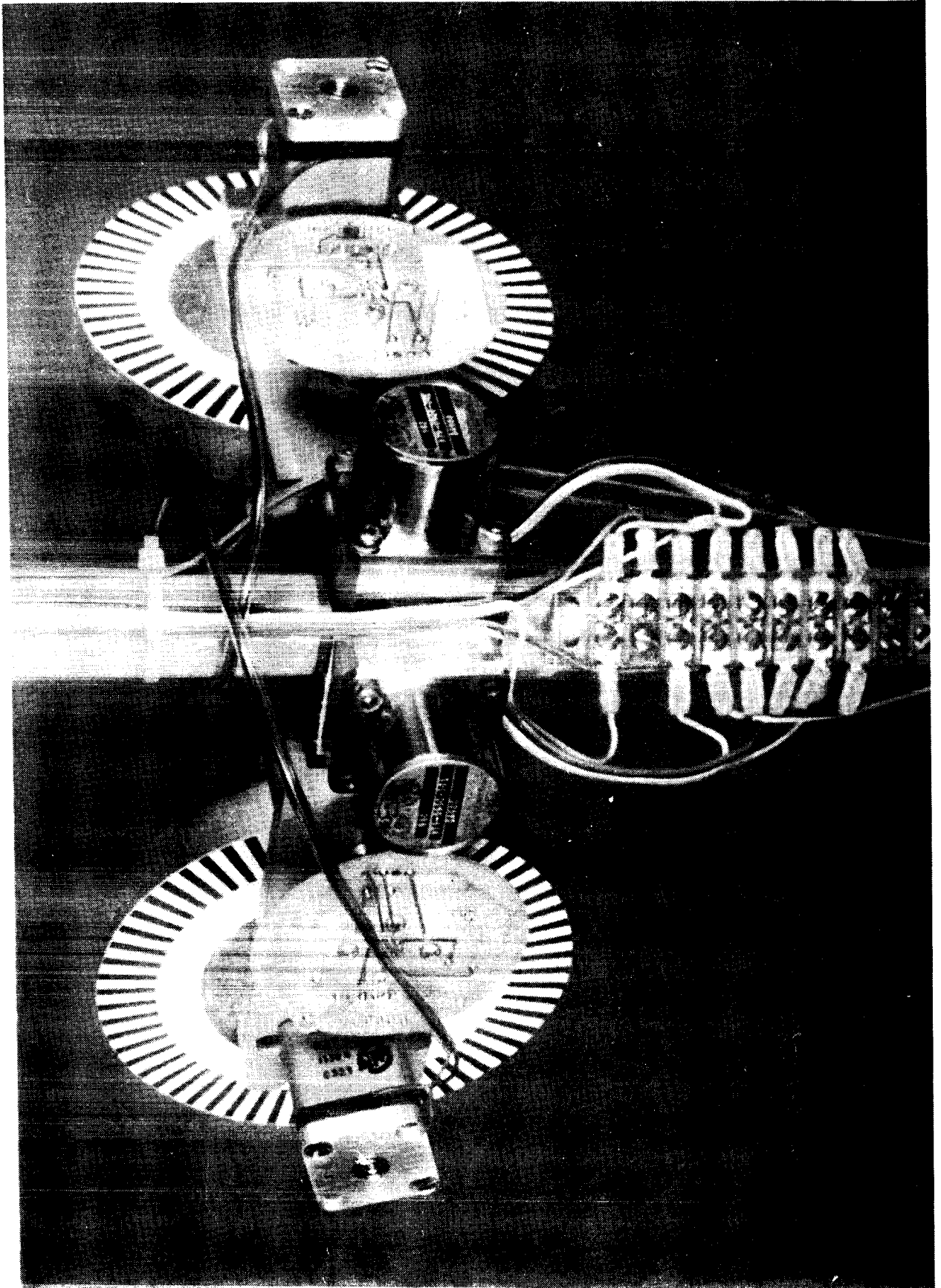
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REACTION WHEELS

The mast-mounted reaction wheels consist of aluminum disks with inertia of about .00027 lb-ft-sec² mounted directly on the drive shaft of a 20 oz-in permanent magnet DC motor. The motors are powered by high bandwidth current amplifiers.

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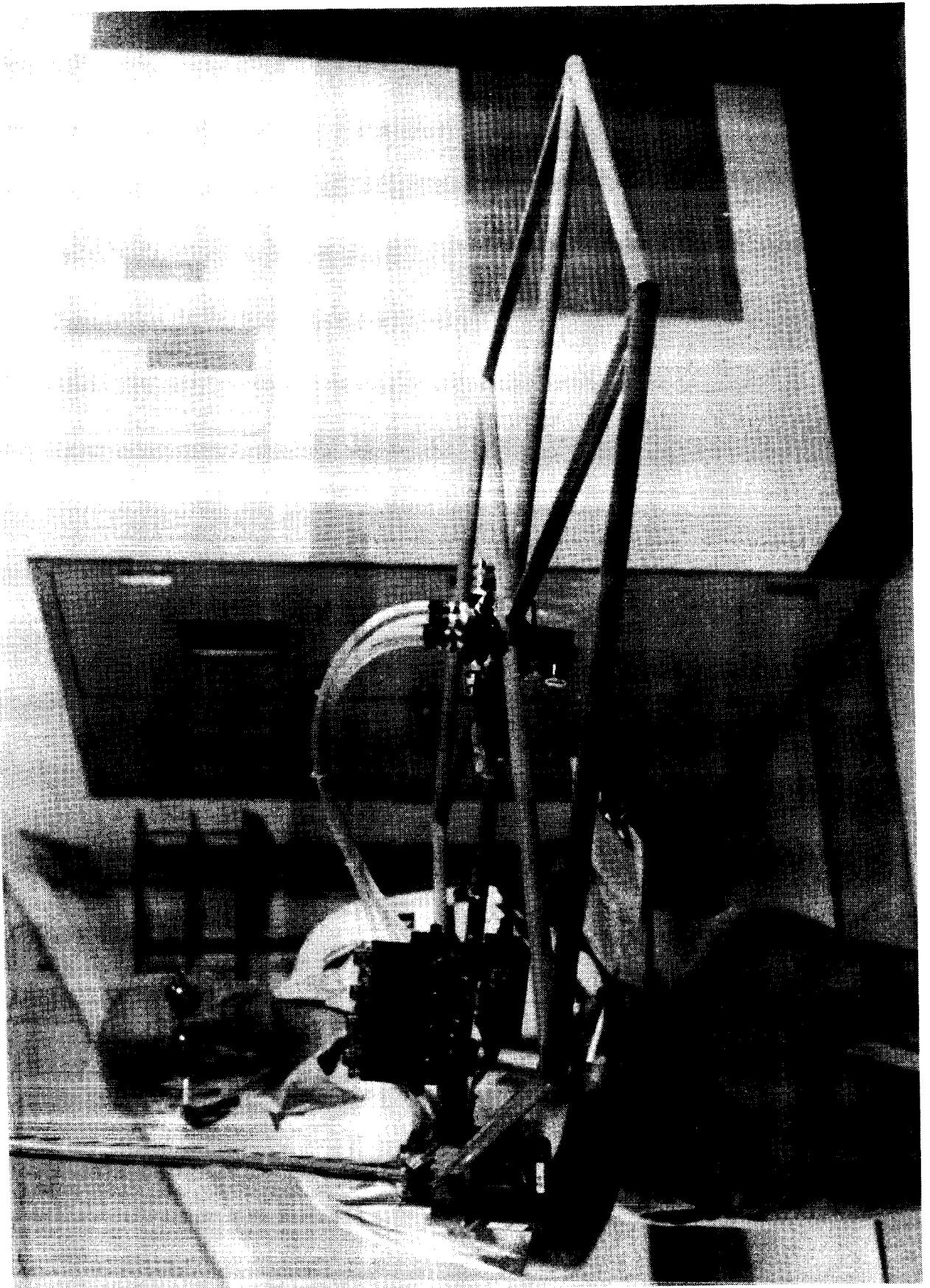
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THRUSTERS

The control forces on the reflector are provided by solenoid actuated cold gas jets. The thrusters are mounted in the center of the reflector and act in the x-y plane. The jets are supplied by a compressed air tank mounted on the shuttle. The pressurized air travels through the mast to the solenoid manifold which gates the air flow between the regulated supply tank and the thrusters. Thrust is initiated by opening the solenoid with a discrete command. The rise time of the thrust to 90 percent is about 20 milli-seconds.

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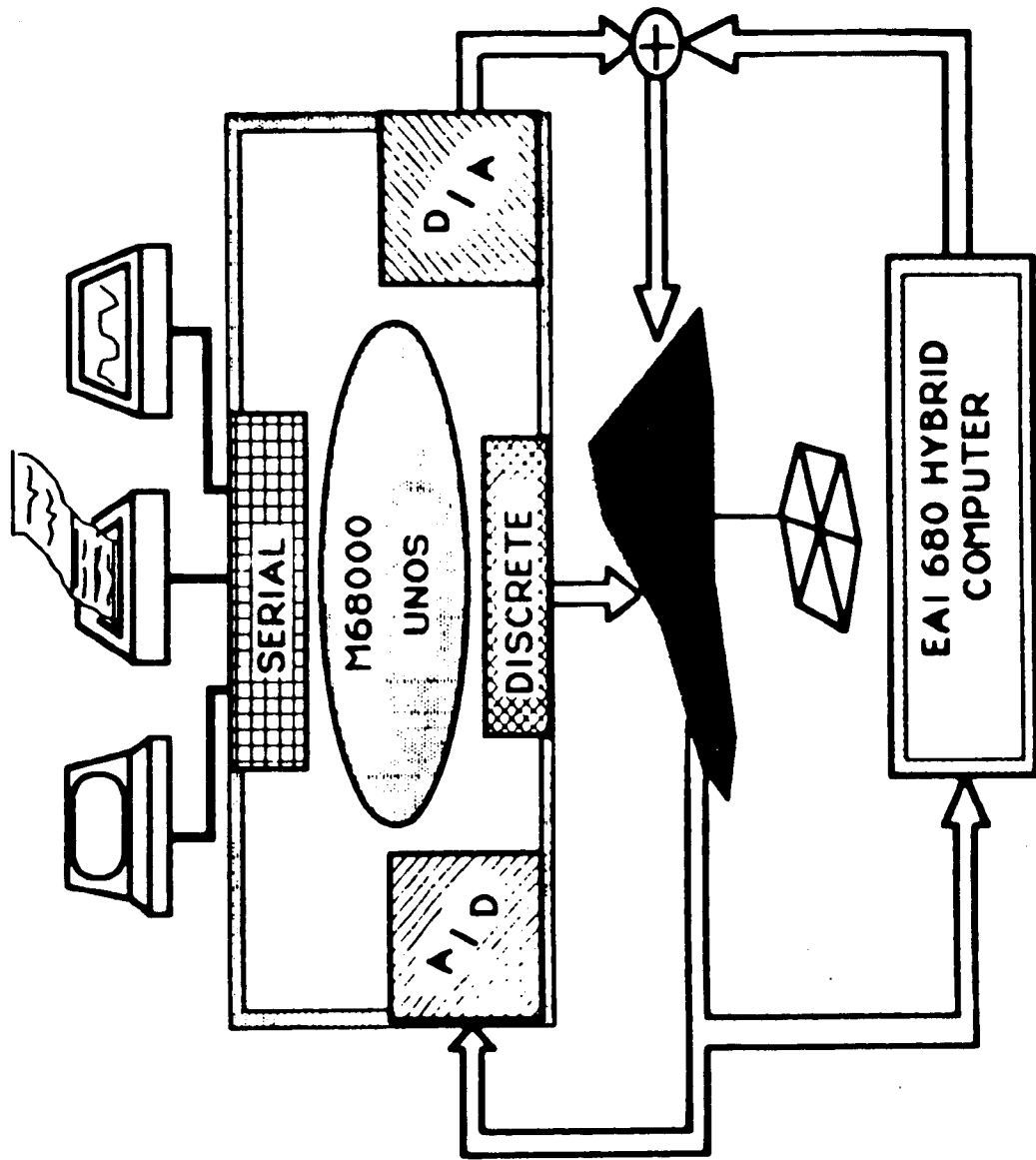
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COMPUTER SYSTEM

The main computer for control law implementation will be a micro-computer based on the Motorola M68000 microprocessor. The computer has 0.5 mbyte of random access memory and a 40 M-byte hard disk. The operating system is based on UNIX with C, Fortran and Pascal compilers available for applications programming. The computer has 12 serial ports and one parallel port. Terminals are connected on two of the ports and an answer-only modem is attached to another. One port is used for an originate-only modem. A line printer is attached to another port.

Analog interfaces consist of a 4 bit output-only discrete channel, 8 digital-to-analog converters and 64 analog-to-digital converters. All converters are 12 bit devices with a range of $\pm 10\text{v}$. Subroutines for accessing the analog interfaces and setting the digital sampling interval are provided.

SCOLE COMPUTER INTERFACES

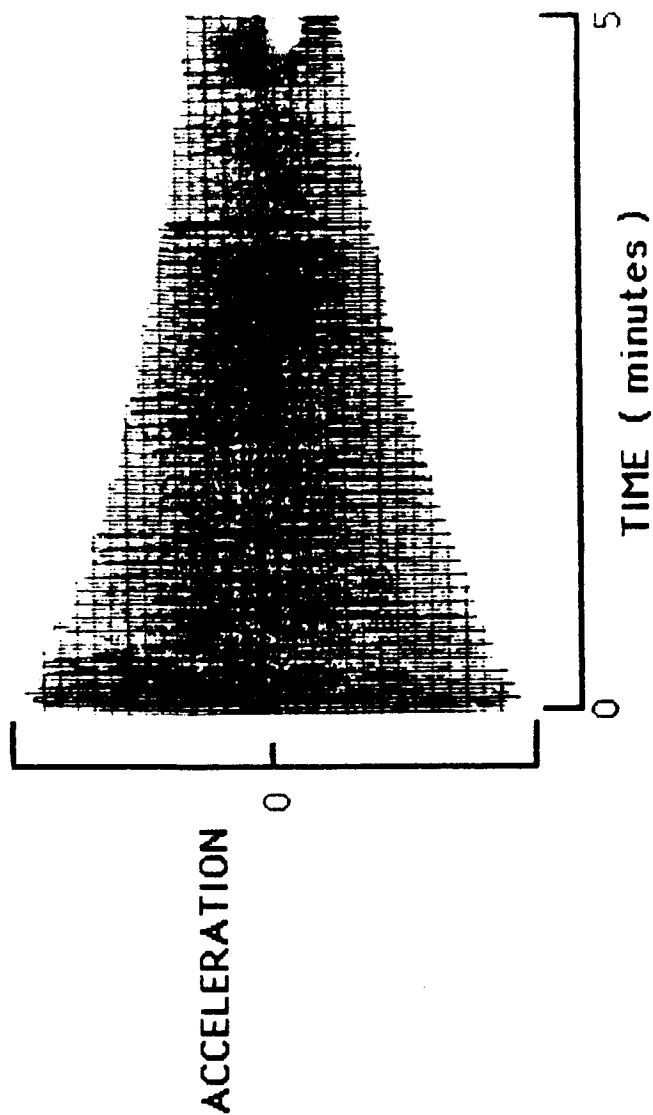
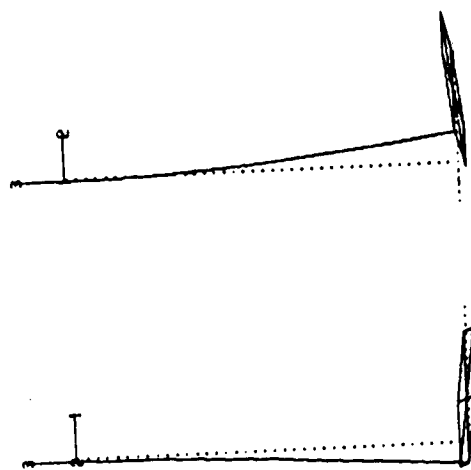
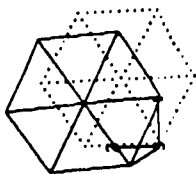


SCOLE DAMPING

The structure is very lightly damped. The slide shows a finite element model of the second flexible mode for a vertical cantilever configuration. The time history of a reflector-mounted accelerometer shows less than 0.1 percent natural damping.

TYPICAL SCOLE DAMPING

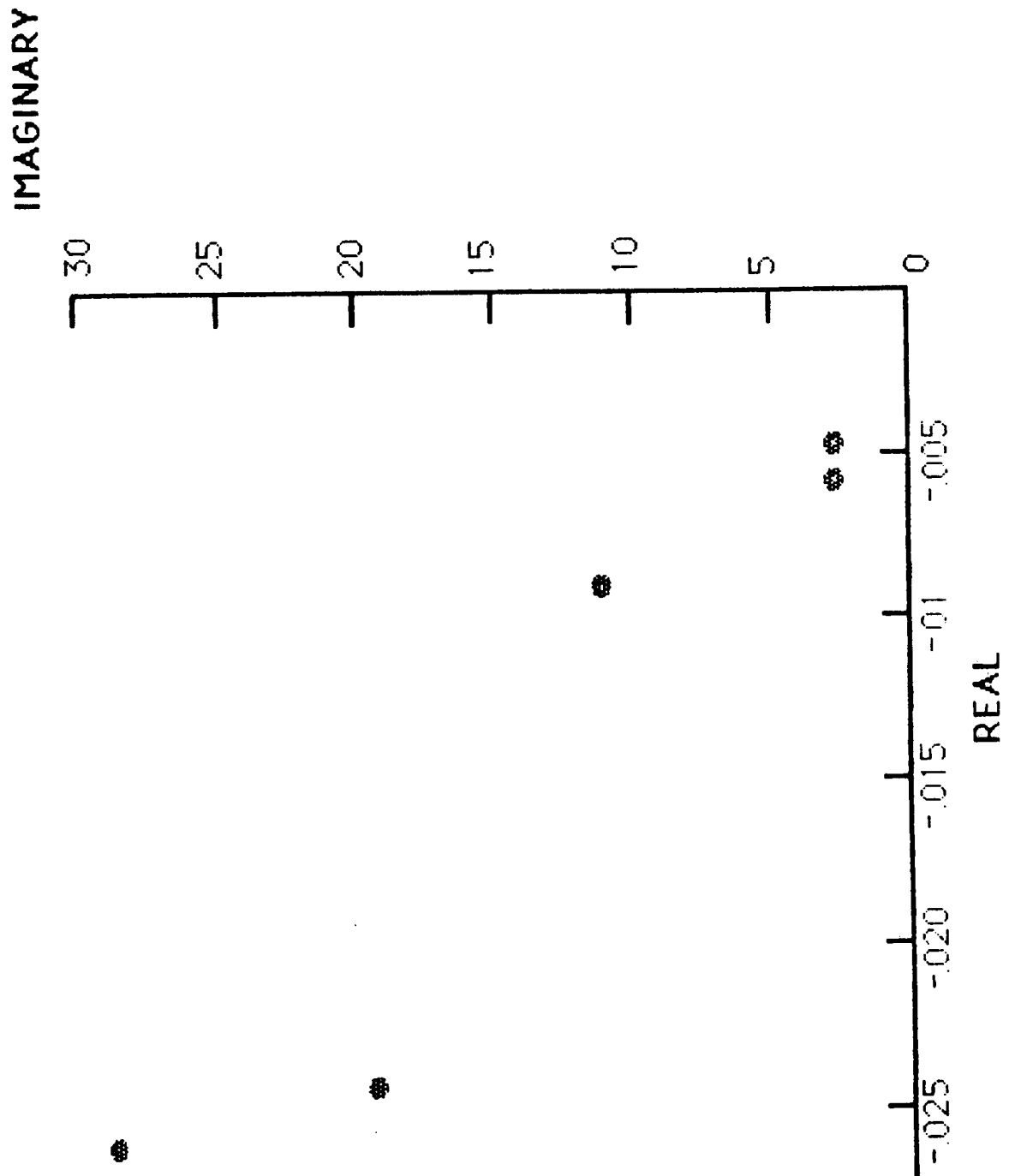
CANTILEVERED MAST - MODE 2
.516 Hz 1% damping



MAST MODES

Experimentally determined frequency and damping for the first five cantilever modes are shown in the slide. The difficulty in modelling the system damping is apparent.

CANTILEVERED MAST ROOTS

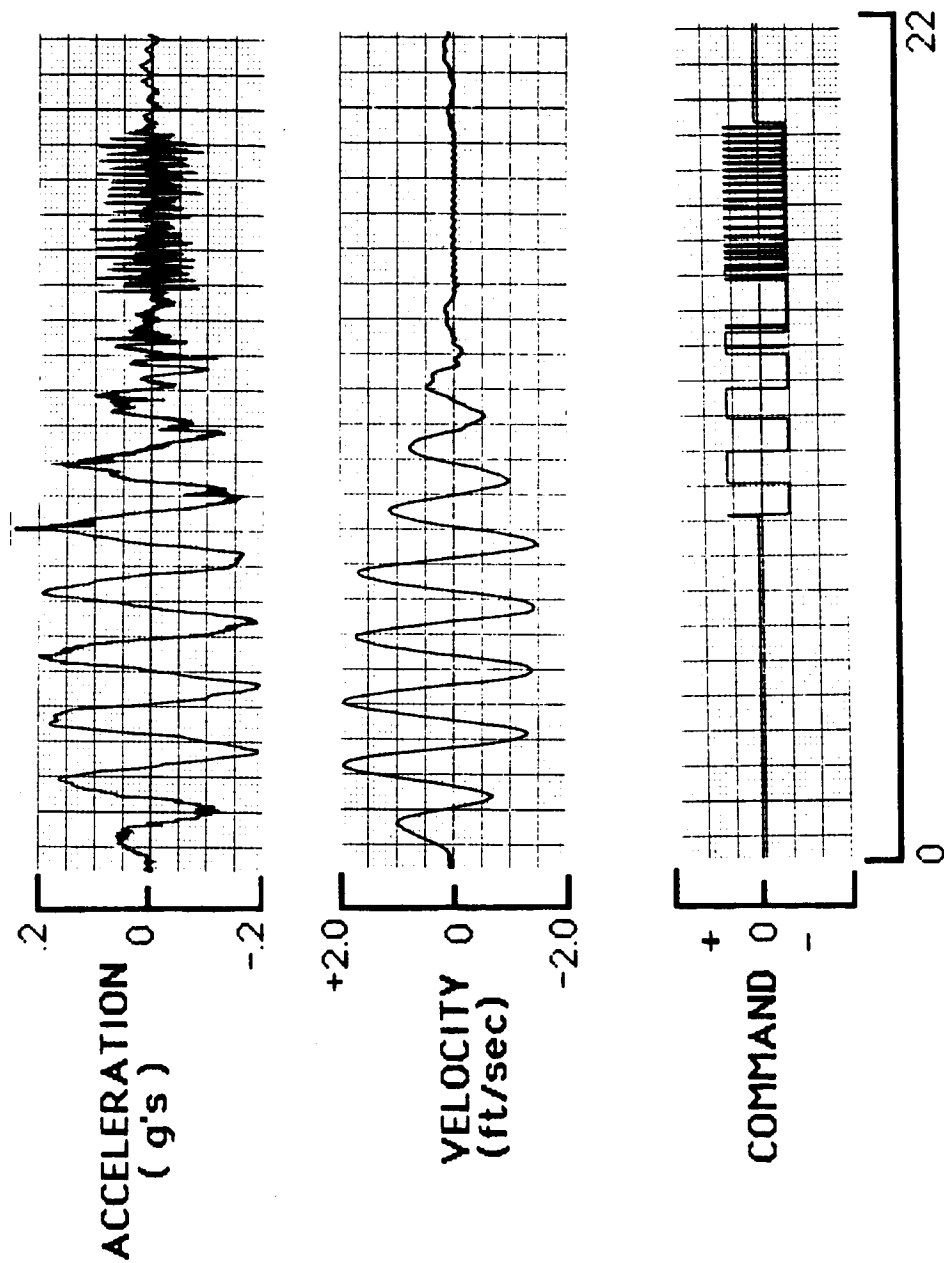


VIBRATION SUPPRESSION

Effectiveness of the thrusters for vibration suppression is demonstrated by the time histories of a reflector-mounted accelerometer, its integral and the thruster command signal. An Euler integration was used to estimate the velocity so the motion started by manually exciting the antenna so the reflector moves along the x-axis. The lower trace shows the command to the $\pm x$ thruster. No compensation is made to stop the limit cycle at the end of the experiment.

SCOLE VIBRATION SUPPRESSION USING ON-OFF THRUSTERS

CANTILEVERED MAST - FIRST MODE



TIME (seconds)

SUMMARY

The SCOLE design challenge was conceived as a common dynamics and control and test-bed for the testing and validation of a variety of control schemes for large flexible structures. The structural configuration and the statement of the control objective are representative of the problems presented by the design concepts of future large satellites.

The laboratory apparatus addresses many of the practical implementation questions and will provide valuable experience with a variety of sensor and actuator types. The experimental hardware is available to interested researchers.

SUMMARY

- * THE SCOPE EXPERIMENT HAS A REALISTIC CONTROL OBJECTIVE
- * THE SCOPE HARDWARE PRESENTS MANY OF THE PRACTICAL IMPLEMENTATION PROBLEMS WHICH WE EXPECT FORM LARGE SPACE STRUCTURES
- * A WIDE VARIETY OF SENSOR AND ACTUATORS ARE AVAILABLE FOR MANEUVER CONTROL AND VIBRATION SUPPRESSION
- * THE EXPERIMENT IS AVAILABLE TO INTERESTED RESEARCHERS